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ISS MINIAERCAM RADIO FREQUENCY (RF) COVERAGE ANALYSIS USING iCAT DEVELOPMENT TOOL

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ABSTRACT

The long-term goals of the National Aeronautics and Space Administration's (NASA's) Human Exploration and Development of Space (HEDS) enterprise may require the development of autonomous free-flier (FF) robotic devices to operate within the vicinity of low-Earth orbiting spacecraft to supplement human extra-vehicular activities (EVAs) in space. Future missions could require external visual inspection of the spacecraft that would be difficult, or dangerous, for humans to perform. Under some circumstance, it may be necessary to employ an *un-tethered* communications link between the FF and the users. The interactive coverage analysis tool (iCAT) is a software tool that has been developed to perform critical analysis of the communications link performance for a FF operating in the vicinity of the International Space Station (ISS) external environment. The tool allows users to interactively change multiple parameters of the communications link parameters to efficiently perform systems engineering trades on network performance. These trades can be directly translated into design and requirements specifications. This tool significantly reduces the development time in determining a communications network topology by allowing multiple parameters to

be changed, and the results of link coverage to be statistically characterized and plotted interactively. To achieve broad spatial RF coverage of communications between the spacecraft (e.g. the ISS) and the FF, multiple antennas may need to be distributed around the spacecraft. The placement of antennas must take into account structural blockage issues posed by the spacecraft itself, whereby the FF may lose communications contact with the users. In order to achieve high operational functionality, such occultation areas need to be minimized. Furthermore, the radio link (both forward and return) must provide sufficient signal strength to maintain communications in the areas around the spacecraft that are to be observed. This includes not only times when the FF and spacecraft antennas are directly aligned with each other (i.e., both antennas are bore-sighted to each other) but also during times when the FF is maneuvering or when the FF is conducting visual searches of the spacecraft structure when there may exist off-axis angle antenna coupling between the two systems. These off-axis pointing situations could have fairly long time durations, and could adversely affect the link signal-to-noise ratio (SNR). The consequences of this could be degradation in quality of services (QoS) being provided to the users. Sufficient link margin is also required during the hand-off phase when the FF traverses the area covered by one antenna on the spacecraft to an area covered by another. An analysis, and subsequent assessment, of the line-of-sight (LOS) blockage and radio frequency communications

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coverage are, therefore, required for systems planning.

One such potential free-flyer that could operate within the ISS external communications coverage area is the mini-Autonomous Extravehicular Robotic Camera (miniAERCam, or MAC), which is a low-volume, low-mass free-flying camera system. This small, spherical "nano-satellite," will be capable of receiving maneuvering commands and transmitting telemetry and video back to astronauts onboard the ISS in lieu of human EVA. The roaming capability of the MAC could be used to supplement video coverage from fixed-location camera systems on the ISS (like the Wireless Video System [WVS] or from cameras mounted on robotic manipulators. Real-time images taken by the miniAERCam would be useful for ISS maintenance, or during berthing operations with the Space Shuttle Orbiter (SSO) and other space vehicles with the ISS.

Analysis of the LOS blockage, and RF link margin coverage was performed for the miniAERCam in the external ISS communications environment. The functional behavior of the ISS miniAERCam communications system is analyzed using the iCAT tool developed at the NASA Johnson Space Center, Engineering Directorate. The software developed enables the systems engineer to perform integrated LOS blockage and RF coverage analysis from a desktop workstation quickly and efficiently in order to provide accurate and mission-critical assessment of the RF coverage and LOS blockage environment as required. The LOS blockage, along with other systems engineering parameters, such as link margin, carrier-to-noise (C/N) ratio, received isotropic power (RIP), and power flux density (PFD) are determined via this software tool which are statistically characterized and visualized in plot form. Data from iCAT can be used to summarize important statistical attributes of the communications network such as the

cumulative distribution function (CDF) of link margin coverage, which can be used to determine operational requirements. This has been performed for the miniAERCam free-flyer. The software tool can also be used to determine potential interference issues with existing systems (such as those onboard the ISS) to aide in the planning of radio spectrum usage.

Initial analysis of the miniAERCam coverage assessment used the WVS Ultra-High Frequency (UHF) antenna locations to determine a baseline analysis for LOS blockage and radio link coverage. The baseline coverage assessment assumed a 2.4 GHz radio frequency link with antennas located at six of the WVS UHF transmitter locations. From this assessment, LOS blockage was found to be less than 3 percent of the total volume around the ISS. The maximum link margin estimates for the forward and return links was found to be 27.8 dB and 20.4 dB, respectively, including LOS blockage. The median value of link margin coverage was found to be 25.8 dB for the forward link and 18.9 dB for the return link (including LOS blockage). While further iterations of the assessment may be required as specific antenna locations (other than WVS UHF locations) for MiniAERCam are defined, the results, nonetheless, indicate the feasibility of the project to work within the vicinity of the ISS, as well as demonstrating the usefulness of the iCAT development tool.

Although demonstrated using the MAC free-flyer as an application to ISS communications planning, the iCAT software tool can be extended to other applications as well. The tool can be used for systems planning, and the development of design specifications, for other systems such as in the mobile cellular industry. On the ground, mobile emitters, in an urban environment, make use of local base stations that are linked to satellites. Integration of LOS blockage with the radio operating parameters (e.g, link

margin, C/N and E_b/N_0) in the terrestrial customer-to-base station link could help define the optimal placement of base stations in the ground network. This is particularly important in an urban environment where minimization of the number of base stations is important to cost savings. The usefulness of the iCAT tool to perform integrated LOS blockage and RF coverage assessment is demonstrated by direct application to the ISS miniAERCam project, which is presented in this paper.

INTRODUCTION

The implementation of systems engineering early in the design process can potentially have a cost-savings benefit to project resources. The first steps in communications network topology design for an external wireless communications system in the near-space environment of the International Space Station (ISS) is presented using a systems engineering approach to the topology layout. The starting point in the analysis to determine the topology layout primarily centers on demonstrating the system feasibility based on line-of-sight (LOS) obstructions due to ISS structural elements and the signal quality of the proposed radio link based on initial transceiver design specifications (e.g., transmit power, antenna gain, link range, etc.). An example of the systems approach to network layout is demonstrated using the interactive coverage analysis tool (iCAT) software and the proposed design parameters for the mini-Autonomous Extravehicular Robotic Camera (miniAERCam, or MAC) free-flyer project.

The iCAT software is an interactive personal computer (PC) desktop tool developed at the NASA/Johnson Space Center to perform coverage analysis of wireless networking systems operating in free space around the ISS. The software is written in Microsoft® Visual Basic, and operates under Microsoft® Excel 97 SR-1. Users can enter

the parameters of their communication systems link budget in the link parameter table located in the *LinkParamTable* worksheet. The nominal (on-axis) link values for the communication systems E_b/N_0 , received isotropic radiated power (RIP), carrier-to-noise ratio (C/N), power flux density in a 4kHz band (PFD_{4kHz}), and link margin (LM) are calculated and displayed in the table. Two-dimensional plots of the field gradients for the RIP, C/N , PFD_{4kHz} and LM are constructed in the ISS coordinate system, at the specified link range, for the both the forward and return link parameters, and are displayed in the *PlotFwd* and *PlotRtn* worksheets for the forward and return links, respectively. The forward and reverse link antenna gain patterns are also constructed and displayed. The cumulative distribution function (CDF) of parameter values is also determined for the selected parameter. Once the input parameters are entered, the User executes the calculations by clicking the *Calculate* button located at the end of the link parameter table. LOS obstruction can also be plotted and incorporated into the gradient plots.

Various wireless robotic free-flyers have been envisioned to work around the ISS to augment extra-vehicular activity (EVA) currently performed by humans. One such free-flyer is the proposed miniAERCam that could be used to take remote imagery of the ISS external structure in areas that would be difficult, or dangerous, for humans to operate. It could also be used to provide additional data for space vehicle docking operations (e.g, for the Space Shuttle Orbiter). The roaming capability, and usefulness, of the MAC could potentially be impaired due to blockages caused by ISS structural components, or by degradation of the radio link signal quality at extended link ranges, and, also to antenna off-axis angle pointing during operations. The MAC free-flyer concept is used as an example to wireless network topology layout design

considerations using the iCAT development software, which is presented in this paper.

THEORETICAL MODEL

For a transmitter located at the center of a sphere with radius, S , the radiated isotropic power, P_t , will uniformly intercept the sphere across its surface. The power flux density (PFD) is defined as the ratio of the intercepted power to the area of the sphere, that is $P_t/4\pi S^2$. If the antenna has transmitting gain, G_t , and taking into account the circuit loss, L_{ct} , between the transmitter and antenna, the PFD (in units $W m^{-2}$) is given by

$$PFD = \frac{P_t G_t L_{ct}}{4\pi S^2} \quad (1a)$$

and, in any 4 kHz frequency band (in dB) is

$$PFD = P_t + G_t + L_s - 10*\log_{10}(B) + 10*\log_{10}(4000) \quad (1b)$$

where, B is the signal bandwidth, and L_s is the spreading loss, $(\lambda/4\pi S)^2$. The product, $P_t G_t$, in equation (1a) is called the equivalent isotropic radiated power (EIRP).

In digital communication systems, the basic equation used to determine the quality of the signal is the ratio of received energy-per-bit to noise-density, E_b/N_o . The received energy, C (also called the carrier signal power), located at a distance, S , from the transmitter is the product of the PFD with the effective area intercepted by the receiver antenna

$$C = \frac{P_t G_t L_{ct} L_{pa} A_r}{4\pi S^2} \quad (2)$$

where A_r is the effective area which is the physical area of the antenna (with diameter, D), $\pi D^2/4$, times the antenna efficiency, η , or $A_r = \pi D^2 \eta/4$, and L_{pa} is the polarization loss in the coupling mismatch between the transmit

and receiver antennas. Substituting the expression for the effective receiver antenna area into equation (2) yields the carrier power (in units W)

$$C = \frac{P_t G_t L_{ct} L_{pa} D^2 \eta}{16 S^2} \quad (3)$$

If the receiver gain, G_r , is defined as the ratio of the effective aperture area, A_r , to the area of a hypothetical isotropic antenna, $\lambda^2/4\pi$ (where λ is the signal wavelength), then

$$G_r = \left(\frac{\pi D^2 \eta}{4} \right) \left(\frac{4\pi}{\lambda^2} \right) = \frac{\pi^2 D^2 \eta}{\lambda^2} \quad (4)$$

Re-arranging equation (4) and solving for $D^2 \eta$, then substituting this into equation (3) yields the following for the carrier signal power

$$C = P_t G_t L_{ct} L_{pa} G_r \left(\frac{\lambda}{4 S \pi} \right)^2 \quad (5a)$$

or,

$$C = P_t G_t L_{ct} L_{pa} G_r L_s \quad (5b)$$

The received energy-per-bit is the product of the received power and bit duration, or

$$E_b = \frac{C}{R} \quad (6)$$

where R is the communication systems bit rate (with units of bits-per-second, or bps), and $1/R$ is the bit duration. The noise at the receiver is generally assumed to have uniform spectral density in the frequency band containing the signal. For the system temperature, T_s , the noise spectral density is given by

$$N_o = k T_s \quad (7)$$

where k is Boltzmann's constant (1.38×10^{-23} J/K) and T_s is in Kelvin (K). Hence, the energy-per bit (which is related to signal quality) is

$$\frac{E_b}{N_o} = \frac{C}{R k T_s} \quad (8a)$$

or,

$$\frac{E_b}{N_o} = \frac{P_t G_t L_{ct} L_{pa} G_r L_s}{R k T_s} \quad (8b)$$

Furthermore, the carrier-to-noise density ratio is given by

$$\frac{C}{N_o} = \frac{E_b}{N_o} + 10 \log_{10}(R) \quad (9)$$

The carrier-to-noise ratio is then, $C/N = C/N_o - 10 \log_{10}(B)$, where B is the signal bandwidth, and is given by

$$\frac{C}{N} = \frac{E_b}{N_o} + 10 \log_{10}(R) - 10 \log_{10}(B) \quad (10)$$

The received isotropic power, RIP, is the carrier signal power, C , as in equation (5b), which can be re-written in terms of the E_b/N_o (using equation (7b) in decibel form) as

$$RIP = \frac{E_b}{N_o} - \frac{G_r}{T_s} - 228.6 + 10 \log_{10}(R) \quad (11)$$

where $\log_{10}(k) = -228.6$ dB.

Finally, the communication systems link margin, LM, is the difference between the expected, or required, E_b/N_o to achieve a desired system bit error rate (BER), for a given modulation and coding scheme, and the calculated E_b/N_o from equation (8b).

The iCAT software tool can be used to calculate the radio link parameters: PFD_{4kHz} , C/N and RIP as per equations (1b), (10), (11), respectively, as well as the LM. Inputs to the software, such as radio link range, system data bit rate, etc. are entered into the *ParamTable*, and the peak values of these parameters are calculated and displayed in the table.

For off-peak values of the link parameters, simulated values of the transmit antenna gain pattern are used. The transmit antenna gain pattern, $G(\theta)$ is simulated based on the user inputs for the 3-dB beamwidth, θ_{3dB} , and the peak gain, G_t , via

$$G(\theta) = G_t - 12 \left(\frac{\theta_{3dB}}{\theta} \right) \quad (12)$$

where θ is the antenna off-axis angle.

The antenna coupling between the transmitter and receiver assumes the range of $G(\theta)$ values for off-axis pointing angles between ± 180 degrees, as given by equation (12), but that the receiver antenna is orientated such that its peak gain is always pointed at the transmitter. This configuration is depicted in figure 1. Two-dimensional plots of the radio link parameters are created via this pointing off-set model. The parameter that is plotted (the PFD_{4kHz} , C/N , RIP, or LM) is selected by the user and is automatically constructed by the iCAT tool.

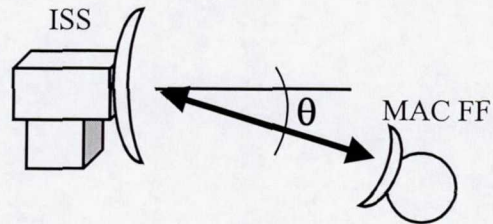


Figure 1: Antenna coupling between ISS antenna and MAC FF. ISS off-axis antenna pointing, MAC FF peak gain pointing.

APPLICATION AND RESULTS

An analysis of the communications environment around the ISS was performed for the MAC using the iCAT software tool. A communications network topology baseline was defined for the analysis, which consists of 6 transceivers distributed around the ISS external structure; these locations correspond to the existing Wireless Video System (WVS) Ultra-High Frequency (UHF) antenna locations (see table 1 for ISS coordinates of locations). The LOS blockage was integrated into the analysis with the radio link parameters LM, C/N, RIP and PFD, which are determined using iCAT, for the free-flyer at a 100 m distance from the center of mass (c.m.) of the ISS. (The LOS blockage was determined via a separate software package and the results were incorporated into the analysis.)

Table 1: Coordinates of Antenna Locations Used for the Analysis in ISS Coordinate System

	description	location (meters)		
		x	y	z
cp01	aft of S3 truss	-3.37	22.72	0
cp05	lower inboard of S1 truss	-0.11	7.16	3.9
cp08	upper outboard of P1 truss	-0.11	-19.56	-3.9
cp10	aft side of P3 truss	-3.37	-22.72	0
cp12	starboard side of Node 1	-7.8	2.75	1.6
cp13	port side of US Lab	5.37	-2.75	1.6

An example of the LOS blockage for the antenna at location cp10 is plotted and shown in figure 2 along with a representation of the ISS structural model at Assembly Complete (AC). In the plot of LOS blockage, the horizontal axis is the degrees of azimuth, as an observer would see from the position of the ISS c.m. In the ISS coordinate system, the direction of flight is along the +X direction, and nadir pointing is in the +Z direction. So, starting from the direction of flight and turning clockwise, as seen from the -Z coordinate, the starboard side of the ISS is found at 90 degrees, aft at 180 degrees and port at 270 degrees. The elevation from the

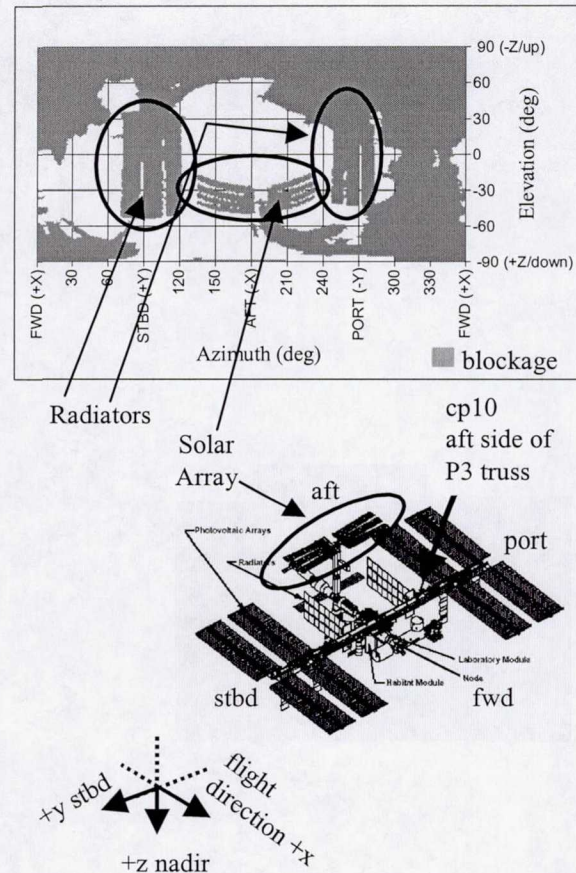


Figure 2: Example of LOS blockage at ISS antenna location cp10. Top is the blockage plot in ISS coordinates, middle is the location of possible structural blockage elements, and bottom is the ISS coordinate vector system.

SS c.m. starts at 0 degrees in the X-Y plane and goes to +90 degrees in the -Z direction, and, likewise, to -90 degrees elevation in the +Z direction. Hence, as seen in the plot, the aft solar array provides a blockage to the antenna between 180 to 210 degrees azimuth and between about -45 to -30 degrees in elevation. Also seen are the obstructions caused by the starboard and port radiators. The LOS blockage at each antenna location was determined, and the composite network blockage was found.

The composite LOS blockage for the network, i.e., the intersection of LOS blockage from all 6 antenna locations concurrently, was determined and the plot is shown in figure 3.

From this plot it can be seen that only a small percentage of the total volume around the ISS is obscured to due structural elements. Possible location of these elements is also shown in figure 3. The LOS blockage for all antenna locations is found to be about 2.3%. This is the percentage of the total volume around the ISS that cannot be viewed from any one of the 6 antenna locations.

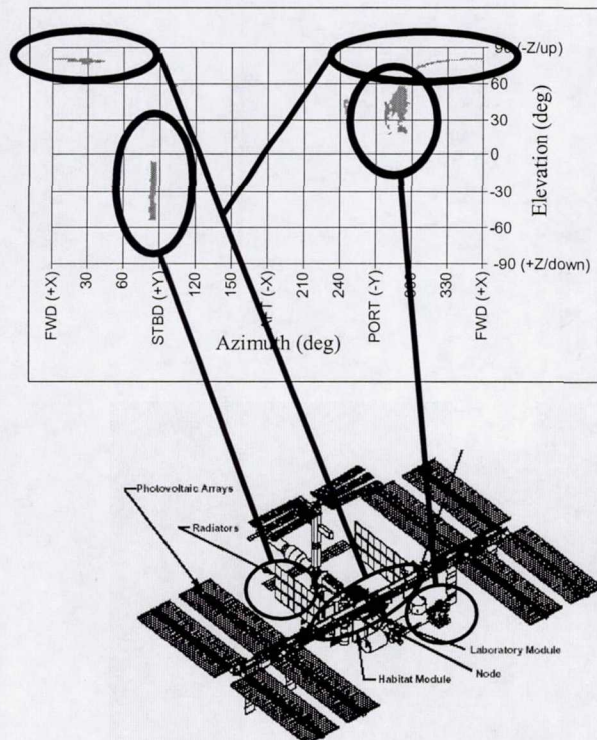


Figure 3: Total system LOS blockage plot (top), and possible structural elements causing the blockage (bottom).

The second part of the analysis consisted of determining the predicted radio link performance of the MAC FF in the vicinity of the ISS. For the radio signal, the forward link is defined as the command channel from the Space Station to the FF and the return link as the data channel from the FF to the Space Station. Plots of the PFD_{4kHz}, C/N, RIP and LM are shown in figures 4-7, respectively for the forward link. A summary of the link parameters is listed in table 2. Similar plots were constructed for the forward and return

links at all 6 antenna locations, but for brevity are not shown. The combined LM spatial field gradient showing the strongest transmitted signal at any location around the ISS is shown in figure 8. The iCAT software can also determine the pointing direction of the antennas, and, the contribution to the LM gradient field from each of the antenna locations is marked at the point where the peak link margin is located for that antenna. The spatial distribution of LM, though not uniform, is apparent in this plot. From a topology viewpoint, it appears that better spacing of the antennas, or better pointing, could result in a more uniform LM coverage. Figure 9, shows the same spatial distribution of LM, but with LOS blockage information

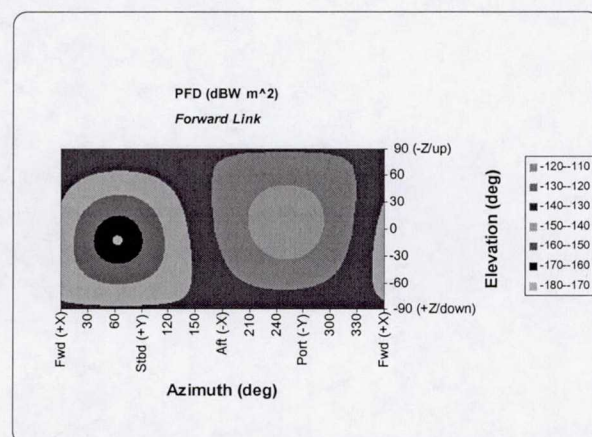


Figure 4: PFD_{4kHz} for antenna at cp10.

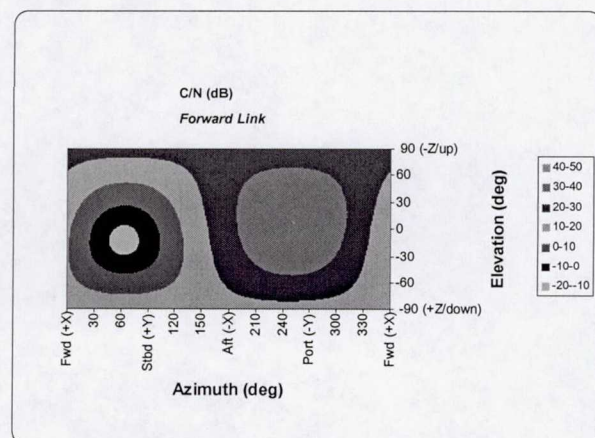


Figure 5: C/N for antenna at cp10.

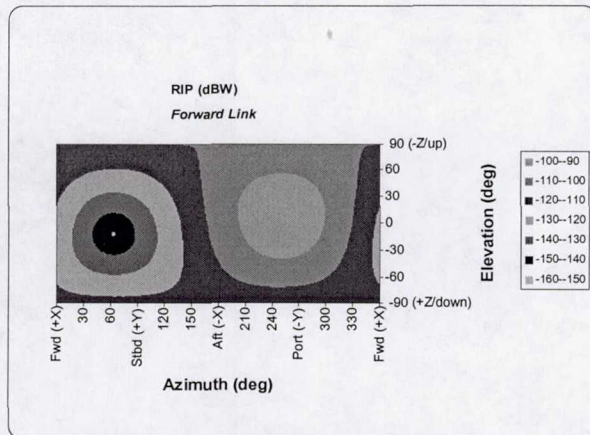


Figure 6: RIP for antenna at cp10.

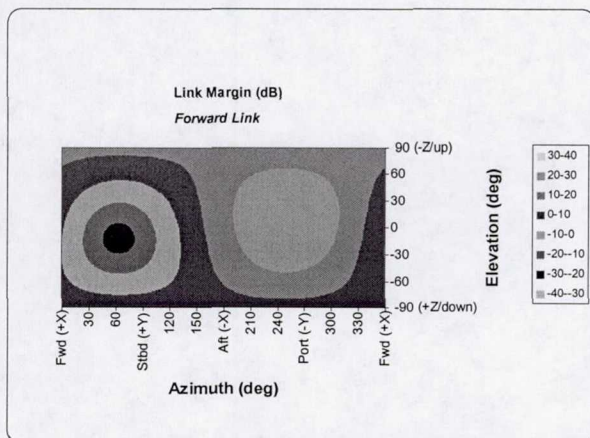


Figure 7: Link margin for antenna at cp10.

Table 2: Summary of Radio Link Parameters for MAC FF Analysis

RF Communication's Feasibility Baseline Model:

- WVS UHV antenna locations
- S-band radio link (2.4 GHz)
- 100 meter link range
- 2 Mbps forward link/command (ISS to FF)/ 10^{-7} BER
- 11 Mbps return link/video & data (FF to ISS)/ 10^{-7} BER
- Transceiver equipment is identical at each ISS location
- Off-axis antenna angles possible for ISS/peak gain for FF

added to the plot. Note that, in this example, the blockage areas do not significantly affect the overall peak LM, as they are primarily located in areas of low LM.

Finally, the CDF of LM coverage for the forward link is shown in figure 10 for the total network coverage. From this it is found that the minimum LM value is 12.8 dB and ahta

the median value is 25.8 dB, and that there exists at least 22 dB LM 73% of the time. That is, 73% of the total coverage volume has a link margin that is at least 22 dB. The CDF was also determined for the case with LOS blockage, and is shown in figure 11. Here, the 2.3% LOS blockage (i.e, no link) shows up in the LM values that are less than 12.8 dB. The minimum, maximum and median LM values were determined for the forward and return links with LOS blockage and without. These quantities are summarized in table 3a and 3b for the forward and reverse links, respectively.

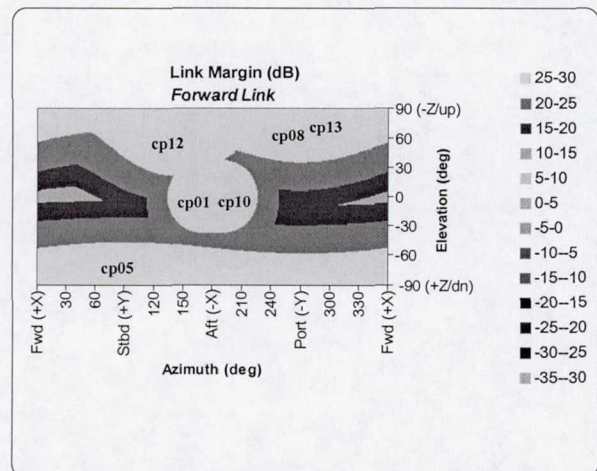


Figure 8: Total system LM without LOS blockage. Also shown are the peak LM areas for each of the ISS antenna locations.

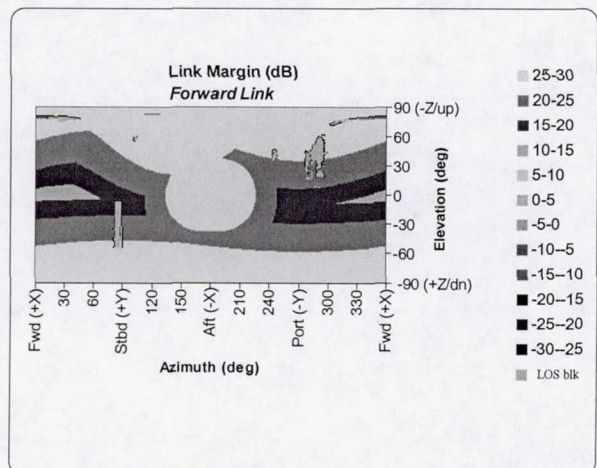


Figure 9: Total system LM with LOS blockage.

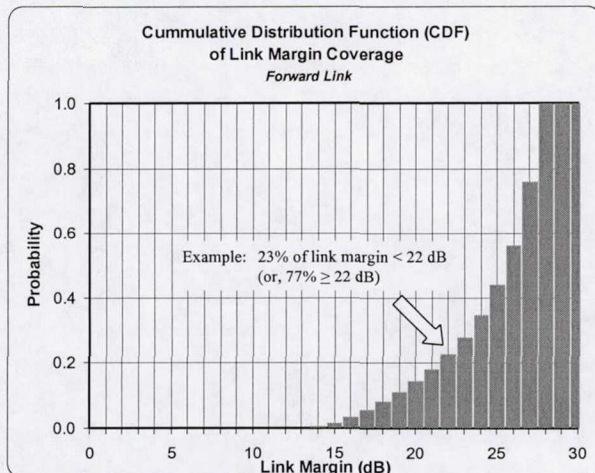


Figure 10: CDF for total system LM without LOS blockage.

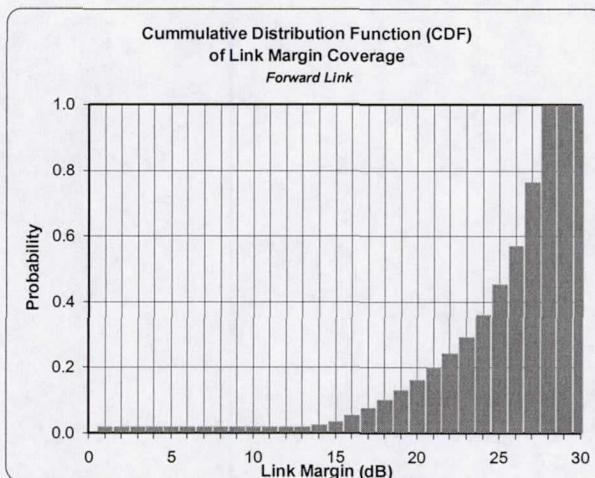


Figure 11: CDF for total system LM with LOS blockage. LOS blockage shows up with probability of 2.3% for LM values less than 12.8 dB.

Table 3b: Summary of Return Link LM Values

	w/o LOS Blockage	w/LOS Blockage
max (dB)	20.5	20.5
min (dB)	9.3	9.3
median (dB)	18.7	18.7

SUMMARY

A software tool has been developed to enable the systems engineer to characterize the wireless network communications environment in terms of the radio systems link margin (LM), power flux density (PFD), carrier-to-noise (C/N) ratio and received isotropic power (RIP). The tool was demonstrated on the miniAERCam (MAC) robotic free-flyer (FF) operating in the external ISS space environment. Line-of-sight (LOS) blockage, due to ISS structural elements, was incorporated into the analysis. The initial findings of the study have demonstrated the feasibility of operating the MAC FF, and the usefulness of the iCAT systems software tool for developing systems requirements for spatial network topology design.

Table 3a: Summary of Forward Link LM Values

	w/o LOS Blockage	w/LOS Blockage
max (dB)	27.9	27.9
min (dB)	12.8	12.8
median (dB)	27.5	25.5